

Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions

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Abstract

This paper explores the influence of key factors such as speed, acceleration, and road grade on fuel consumption for diesel and hydrogen fuel cell buses under real-world operating conditions. A Vehicle Specific Power-based approach is used for modeling fuel consumption for both types of buses. To evaluate the robustness of the modeling approach, Vehicle Specific Power-based modal average fuel consumption rates are compared for diesel buses in the US and Portugal, and for the Portuguese diesel and hydrogen fuel cell buses that operate on the same route. For diesel buses there is similar intra-vehicle variability in fuel consumption using Vehicle Specific Power modes. For the fuel cell bus, the hydrogen fuel consumption rate was found to be less sensitive to Vehicle Specific Power variations and had smaller variability compared to diesel buses. Relative errors between trip fuel consumption estimates and actual fuel use, based upon predictions for a portion of real-world activity data that were not used to calibrate the models, were generally under 10% for all observations. The Vehicle Specific Power-based modeling approach is recommended for further applications as additional data become available. Emission changes based upon substituting hydrogen versus diesel buses are evaluated.

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1. Introduction and background

There is growing interest in the use of alternative fuels and propulsion systems for highway vehicles. Among highway vehicles, transit buses have been a focal point for development of zero- and near-zero-emissions fuel

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cell technology (Eudy and Parish, 2001). Thus, there is a need to characterize baseline fuel use of conventional diesel transit buses and to develop a consistent methodology that can be used to compare buses of various fuel types and propulsion systems.

Bus fuel consumption and efficiency are highly dependent on vehicle and engine attributes. Passenger load, travel speed, the number of stops, road grade and the frequency of traffic interruptions affect fuel consumption (Ang and Fwa, 1989). Quantitative exploration of the effects of these factors on fuel consumption is needed to develop methods and strategies for fuel consumption prediction and fuel economy improvement.

Two general approaches are usually considered in modeling fuel consumption and emissions: physically based analytical models and empirically based models. Examples of physically based modeling approaches applicable to transit buses include EcoGest and the Physical Emissions Rate Estimator (PERE). The main inputs of EcoGest include vehicle characteristics, number of passengers, roadway characteristics and a synthetic speed profile. EcoGest is capable of estimating instantaneous as well as trip average fuel consumption and emissions (Silva et al., 2006). PERE uses vehicle parameters and second-by-second driving traces as input, and estimates second-by-second fuel consumption rates (Nam and Giannelli, 2005). PERE is based upon the assumption that fuel consumption rates for diesel and gasoline vehicles, such as passenger cars and diesel buses, are determined by vehicle specific power (VSP), engine speed, engine displacement volume, vehicle mass, and other factors.

The empirically based modal approach is exemplified by the MOVES2004 model released by the US Environmental Protection Agency (EPA). MOVES2004 can estimate energy consumption for transit buses (Environmental Protection Agency, 2005). Power demand is a key variable that explains fuel consumption and emission rates (Jimenez-Palacios, 1999). VSP, a surrogate for power demand, has been used for emissions estimation for light-duty gasoline vehicles and diesel transit buses (Frey et al., 2002; Zhai et al., 2006). MOVES2004 and PERE are complementary models. Where possible, MOVES2004 is based on second-by-second measurements of vehicle fuel use and emissions obtained either using dynamometers in a laboratory or from real-world measurements from Portable Emissions Measurement Systems (PEMS). Where such data are not available, PERE may be used to fill data gaps in MOVES2004 energy consumption rates.

An example of the use of PEMS data was a study conducted by EPA, where city transit buses operated by the Ann Arbor Transit Authority (AATA) were monitored. Both fuel consumption and emission measurements were taken while buses were driven on their established routes (Environmental Protection Agency, 2002).

Hydrogen fuel cell buses have been proposed as an environmentally friendly alternative to conventional buses, since they have the potential for eliminating tailpipe emissions (Vandenborre and Sierens, 1996). The Clean Urban Transport for Europe (CUTE) Project encompassed the implementation and evaluation of both a hydrogen fuel infrastructure and fuel cell vehicles in nine participating European cities (Haraldsson et al., 2005). While life cycle-based evaluation models of hydrogen-fueled vehicles, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, have been reported (Wang, 2001), few studies regarding fuel consumption and emissions reductions under real-world traffic conditions have been carried out.

2. Objectives

The principal objectives are to: evaluate factors that significantly affect transit bus fuel consumption under real-world operating conditions; develop a conceptual approach for modeling vehicle specific fuel consumption at a micro-scale taking into account key operational factors; assess differences in fuel consumption for diesel buses in the US and Portugal to evaluate the transferability of the modeling approach; compare fuel consumption for diesel and hydrogen fuel cell buses that operate on identical routes; and estimate emission changes from substitution of hydrogen-fueled buses for diesel buses.

3. Database and description

The bus databases uses data provided to the research team by EPA that were collected in cooperation with the Ann Arbor Transportation Authority (AATA) for 12 diesel transit buses and data collected in the city of

Porto, Portugal as part of the CUTE Project and provided by the Instituto Superior Técnico (IST) of Lisbon, Portugal, for both diesel and hydrogen fuel cell buses.

3.1. *Ann Arbor Transportation Authority A database*

On-board data for diesel transit buses in Ann Arbor were gathered using PEMS installed on 12 diesel transit vehicles, while they traveled on their regular routes (Environmental Protection Agency, 2002). The routes differed by vehicle, since a particular vehicle typically had a unique route assignment. The tested buses included New Flyer models with Detroit Diesel Series 50 engines. All buses weigh 12 tonnes and have 8.5 l engines. Four of these vehicles are 1995 model year and the others are 1996 model year. The PEMS used was a SEMTECH-D manufactured by Sensors Inc. The PEMS includes an engine scanner for recording data from the vehicle's electronic control module (ECM); a GPS unit for recording vehicle position and altitude; gas analyzers for measuring pollutant concentrations in the exhaust; exhaust probe and sample hose; weather probe; and a computer for combining these data streams into one file and estimating emission rates on a mass per time basis. The ECM provided real-time volumetric fuel consumption rate data that were converted to a mass flowrate. From the exhaust concentration data, fuel-based pollutant emission rates can be estimated (i.e. in terms of mass of pollutant per mass of fuel consumed). The latter two quantities are multiplied to arrive at mass per time emission rates. The data for the AATA buses are reported on a second-by-second basis. There are 2520–8640 s of observations for each of the 12 buses.

3.2. *Porto database*

For both diesel and fuel cell buses, the tested bus routes in Porto have substantial road grades (up to 10%) and low average speed. The route length is 7.8 km and is entirely urban. Data were collected on one line of the Sociedade de Transportes Colectivos do Porto (STCP) network. This route is circular without a terminal stop and has constant circulation. Data were collected for both vehicles on 1 day from approximately 6:30 a.m. to 6:00 p.m., which covered a variety of traffic conditions. One hydrogen fuel cell bus and one diesel bus traveled on this route, in the same direction, during the same time period and from the same starting point under similar ambient conditions.

The Porto diesel bus tested in 2004 is a 2002 Mercedes Citaro with a 12 l engine. The bus weight was 11.5 tonnes. There were 14 measured trips for the diesel bus. The bus was equipped with a second-by-second data collection measurement system that consisted of a fuel flowmeter, a command/display unit, a data acquisition board and a laptop computer. Vehicle dynamics were recorded, including vehicle speed and fuel consumption rate. A global positioning system (GPS) unit with a barometric altimeter was used to track the route and its topography. The monitoring system allowed the bus to run its regular route, with minimal interference to its normal duty cycle. Passenger counts were manually recorded.

The tested fuel cell bus was a small series production Mercedes Citaro that weighs approximately 14 tonnes. Two fuel cell stacks were fed from 350 bar compressed hydrogen storage that had a combined power of 300 kW. Electric current was sent to a 200 kW electric engine that drove a conventional gearbox. The bus was not a hybrid. The minimum power output of the fuel cell was approximately 25 kW. During idling and low loads, some power was dumped into a cooling system. This arrangement is clearly not the most efficient, but was adopted to simplify the vehicle design and ensure the reliability needed for regular operation for purposes of a demonstration vehicle. There were 11 measured trips. For each trip, vehicle speed, fuel consumption rate and controller area network (CAN) motor RPM were recorded twice per second.

Each of the AATA diesel buses, Porto diesel bus, and Porto hydrogen fuel cell bus databases were divided into a calibration and validation dataset. The calibration data sets were used to develop VSP-based modal fuel consumption models. The models were applied to the activity data of the validation datasets to predict fuel consumption, and the predicted and actual fuel consumption were compared to quantify the error in the model estimates. Overall, about 60–70% of data for each type of vehicle were used for model calibration. For the AATA diesel database, eight buses were selected for the calibration dataset and four buses were selected for the validation dataset. These data sets have similar distributions of vehicle speed, acceleration and road grade. For the Porto diesel bus, nine trips were selected for the calibration dataset and five trips were

selected for the validation dataset. For the Porto fuel cell bus, eight trips were selected for calibration and three trips were selected for validation. For the Porto buses, each of the calibration and validation datasets for both vehicles included trips that occurred in the morning and the afternoon. Therefore, these latter datasets incorporate a similar range of traffic and environmental conditions.

4. Methodology

The methodology consisted of: (a) conducting an exploratory analysis to assess the relationships between fuel consumption and factors that significantly affect it; (b) developing a VSP-based approach for estimating fuel consumption at a micro-scale level; (c) comparing fuel consumption between different vehicles for a given fuel (i.e. diesel); (d) comparing fuel consumption between buses with differing fuel types; and (e) developing fuel-based emission factors to evaluate tailpipe emission reductions for hydrogen-fueled buses.

Various trip-based factors affect the amount of fuel that is consumed during a vehicle's real-world duty cycle. These include speed, acceleration and road grade. In addition, passenger load on transit vehicles could impact fuel consumption. Spearman's rank correlation is used to assess whether a statistically significant monotonic relationship exists between fuel consumption and each of these factors. In addition, fuel consumption rates for diesel buses are stratified into categories according to speed and on-board passenger load to compare fuel consumption for different passenger loads at a given range of speed. The key variables affecting vehicle fuel consumption identified in the exploratory analysis constituted the basis for the development of a modeling approach.

VSP takes into account aerodynamic drag, tire rolling resistance and road grade. VSP is generally defined as power per unit mass of the vehicle and is a function of vehicle speed, acceleration, and road grade. VSP for transit buses were estimated based on typical coefficient values that are representative of the types of buses that are analyzed here (Andrei, 2001; Zhai et al., 2006):

$$\text{VSP} = v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3 \quad (1)$$

where VSP is the Vehicle Specific Power (m^2/s^3); v is instantaneous speed at which the vehicle is traveling (m/s); a is instantaneous acceleration of the vehicle (m/s^2); φ is instantaneous road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient. VSP was estimated for each second of measured in-use data.

The in-use data were stratified based on ranges of VSP to define VSP-based modes. Average fuel consumption rates were calculated for each mode. Two considerations were taken into account when determining the number of discrete VSP modes: (a) each mode should produce an average fuel consumption rate that is statistically different from any other mode and (b) no single mode should dominate the estimate of total fuel consumption. These criteria yielded a total of eight VSP modes. The definition of each mode is given in Table 1 (Zhai et al., 2006). Although the modal definitions were developed based on data from the AATA buses, the same mode definitions were used for all buses (including those from Porto) to facilitate comparisons. The same approach was adopted for all calibrations.

The calibration data were utilized to estimate VSP-based modal average fuel consumption rates. Trip-based fuel consumption was estimated as:

$$E = \sum_{j=1}^J \text{FR}_j \times \text{TVSP}_j \quad (2)$$

Table 1
Definition of Vehicle Specific Power (VSP) modes

VSP mode	VSP range (m^2/s^3)	VSP mode	VSP range (m^2/s^3)
1	$\text{VSP} \leq 0$	5	$6 \leq \text{VSP} < 8$
2	$0 < \text{VSP} < 2$	6	$8 \leq \text{VSP} < 10$
3	$2 \leq \text{VSP} < 4$	7	$10 \leq \text{VSP} < 13$
4	$4 \leq \text{VSP} < 6$	8	$\text{VSP} \geq 13$

Source: Zhai et al. (2006).

where E is the total trip fuel consumption (in liters for diesel buses and in grams for hydrogen buses); j the VSP mode index, J is the number of VSP modes ($J = 8$ for diesel buses and 6 for hydrogen buses as explained later); FR_j is fuel consumption rate for VSP mode j (l/s for diesel bus and g/s for hydrogen bus); and $TVSP_j$ is the bus trip time spent in VSP mode j (s).

For purposes of model validation, the total trip fuel consumption was estimated based upon the validation datasets for AATA buses, and Porto diesel and hydrogen buses. Trip-based fuel consumption estimation errors were quantified through comparisons with measurements of total fuel consumed.

The magnitude and variability in average fuel consumption between AATA and Porto diesel buses, and between the Porto diesel and hydrogen fuel cell bus are compared. To compare fuel consumption for diesel and hydrogen fuels, the fuel consumption for diesel was converted to an equivalent hydrogen-basis. The conversion was done based on lower heating values of 120 MJ (MegaJoule)/kg for hydrogen and 35.7 MJ/l for diesel (Chandler and Eudy, 2006).

The effect of substituting diesel buses with hydrogen-fueled buses on air quality was evaluated based upon the estimation of fuel cycle and tailpipe emissions. Fuel cycle refers to the “well-to-pump” stage commonly referred in fuel life cycle analysis. Currently, the most likely fuel pathway for producing hydrogen is steam reforming of natural gas. The GREET model was used to estimate fuel cycle energy consumption in units of Btu per MMBtu of hydrogen or diesel and emissions of volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO₂) in units of grams per MMBtu for both hydrogen and diesel fuels (Wang, 2001). The diesel fuel cycle emissions rates were converted to an equivalent hydrogen-basis for emission comparisons.

In a previous study, tailpipe average emission rates in grams per second were estimated for hydrocarbons (HC), CO, NO_x, and CO₂ using a VSP modal approach based upon the AATA database (Zhai et al., 2006). VSP modal average fuel consumption rates in liters per second were also estimated. Fuel-based average emission rates were developed using time-based emission rates divided by corresponding fuel consumption rates. Fuel-based average emission rates for diesel buses were further converted to an equivalent hydrogen-basis to evaluate emission tailpipe reductions by substituting hydrogen-fueled for diesel buses.

Only one real-world driving cycle in the hydrogen-fueled bus database was used to evaluate differences in energy consumption and differences in emissions based on substitution of a hydrogen for diesel bus.

5. Results

5.1. Exploratory analysis

The exploratory analysis was applied to the combined dataset. Table 2 shows Spearman correlation coefficients for fuel consumption rate and selected explanatory factors for all tested vehicles. All p values are less than 0.05, indicating that all correlation coefficients are statistically significant. Speed and acceleration are highly correlated with fuel consumption for both diesel and hydrogen fuel cell buses. The correlation coefficients for speed and fuel consumption rates are higher for diesel than for hydrogen buses, indicating a stronger effect for the former. Road grade is weakly correlated with fuel consumption for both types of buses.

The effect of on-board passenger load was explored for one diesel bus because such data were only available in Porto. Five speed bins including idle, and three levels of on-board passenger load defined speed and passenger load categories. As shown in Fig. 1, passenger load has a significant effect on fuel consumption, particularly at the middle and high-speed ranges. However, as expected, passenger load has almost no effect on fuel consumption during idling, or under very low speeds (≤ 10 km/h).

Table 2
Spearman rank correlation for fuel consumption rates versus selected factors based upon the combined trip database

Data source	Fuel type	Speed	Acceleration	Road grade
AATA	Diesel	0.59	0.66	0.11
Porto	Diesel	0.79	0.32	0.10
	Hydrogen	0.49	0.40	0.21

5.2. Fuel consumption modeling results using VSP approach

Real-world speed profiles, from which vehicle acceleration can be estimated, were combined with road grade data from the vehicle routes to estimate second-by-second VSP using Eq. (1). Dynamic fuel consumption rates were grouped into micro-VSP bins of size $1 \text{ m}^2/\text{s}^3$ to ascertain their relationship to VSP for both diesel and hydrogen fuel cell buses. As shown in Figs. 2a and 3a, average fuel consumption rates are similar when VSP values are less than zero; however, an approximately monotonic increase in fuel consumption rate is noted for both diesel and fuel cell buses, as VSP increases up to a critical value of about $10 \text{ m}^2/\text{s}^3$. Beyond that point, changes in average fuel consumption rate dampen considerably while the variability significantly increases. The vertical lines in Figs. 2 and 3 represent 95% confidence intervals (CI) on the mean. The widest fuel consumption rate confidence intervals are associated with high VSP values because few such samples are available in the calibration dataset.

Using the eight VSP modes in Table 1, a driving pattern was modeled according to the distribution of time spent in each VSP mode. Average fuel consumption rates corresponding to each of the VSP modes were estimated for the diesel and fuel cell buses based upon the individual calibration datasets. These estimates are depicted in Figs. 2b and 3b. In general, average modal fuel consumption estimates increase monotonically with VSP, although there is an exception for mode 8 for the Porto diesel bus. For the hydrogen fuel cell bus, VSP modal average fuel consumption rates are statistically indistinguishable for modes 6 and higher. The ratio of the highest to lowest mean value among the modes is 10.8, 10.3 and 4.4, for AATA diesel buses, the Porto diesel bus, and the Porto fuel cell bus. A large ratio indicates larger inter-modal variability in fuel consumption over the course of the trip.

Trip-based fuel consumption was estimated based upon the calibration dataset. The R^2 values for the VSP-based models for the calibration data are 0.70 for AATA diesel buses, 0.90 for the Porto diesel bus, and 0.61 for the Porto hydrogen fuel cell bus. Thus, the VSP-based approach is able to explain a substantial portion of the short-term variability in fuel consumption.

The ability of the VSP modal method to predict total fuel consumption for a trip was evaluated. The calibration dataset was used to estimate mode-specific fuel consumption rates and the validation dataset is used to evaluate the predictive ability of the VSP model. For the fuel cell bus, modes 6–8 were combined into one mode with $\text{VSP} \geq 8 \text{ m}^2/\text{s}^3$ because of similarities in average fuel consumption. Based on the time spent in each of the VSP modes in a given trip, total trip fuel consumption was estimated using Eq. (2). The prediction errors between measured and predicted total trip fuel consumption are summarized in Table 3. For AATA diesel buses, the errors range from -9.5% to 10.6% . For the Porto diesel bus, the errors range from -8.7%

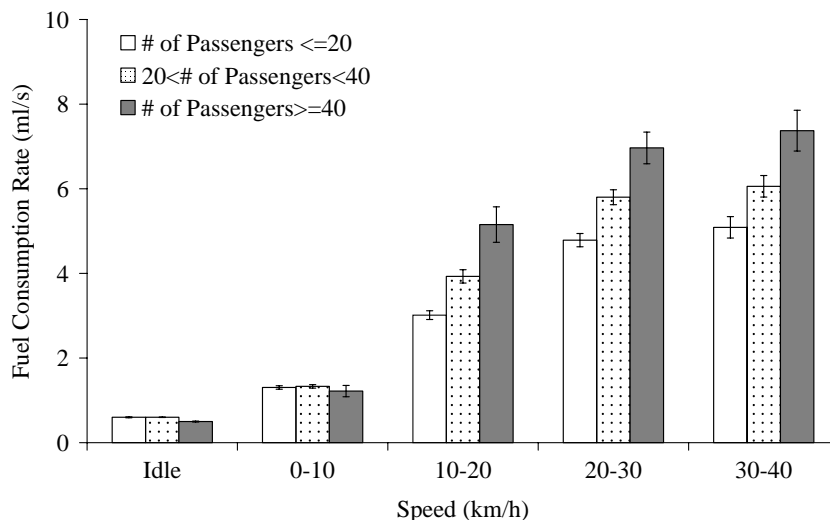


Fig. 1. Effect of on-board passenger load on mean fuel consumption rate, with 95% confidence intervals for Porto diesel bus.

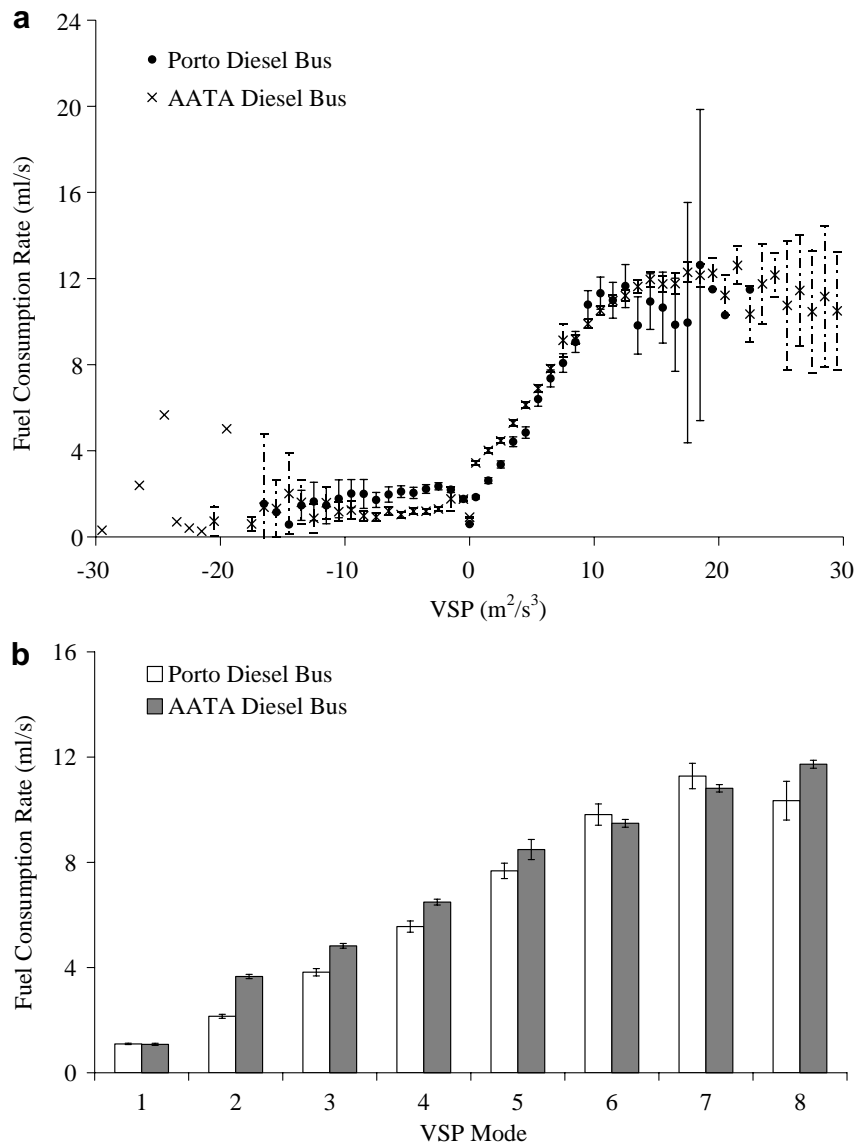


Fig. 2. Fuel consumption rate by VSP mode for Ann Arbor and Porto diesel buses: (a) diesel buses VSP and average fuel consumption, with 95% confidence intervals and (b) VSP modal average fuel consumption rate, with 95% confidence intervals, for diesel buses.

to 9.0%, whereas for the hydrogen fuel cell bus, the errors range from -0.8% to 2.6% . These errors are considered to be reasonable and indicate that the VSP approach is capable of providing good predictions of trip-based fuel consumption for transit buses that span various engine technologies.

The calibration data from the Porto bus for which passenger counts were available were used to develop a VSP-based model that is further stratified by ranges of passenger load. As shown in Fig. 4, with the exception of modes 1 and 2, higher passenger loads result in higher fuel consumption, especially at the higher VSP modes. Total trip fuel consumption was estimated based on both the fraction of time spent in each VSP mode and associated passenger load mode. As shown in Table 3, the trip prediction errors range from -6.4% to 4.4% , which are reasonable and consistently lower than the range of errors obtained by the VSP-only approach (-7.3% to 9%).

Modal fuel consumption rates were compared among the diesel buses. Fig. 2b shows that both the AATA diesel buses and the Porto diesel bus exhibit similar trends. For example, modal average emission rates

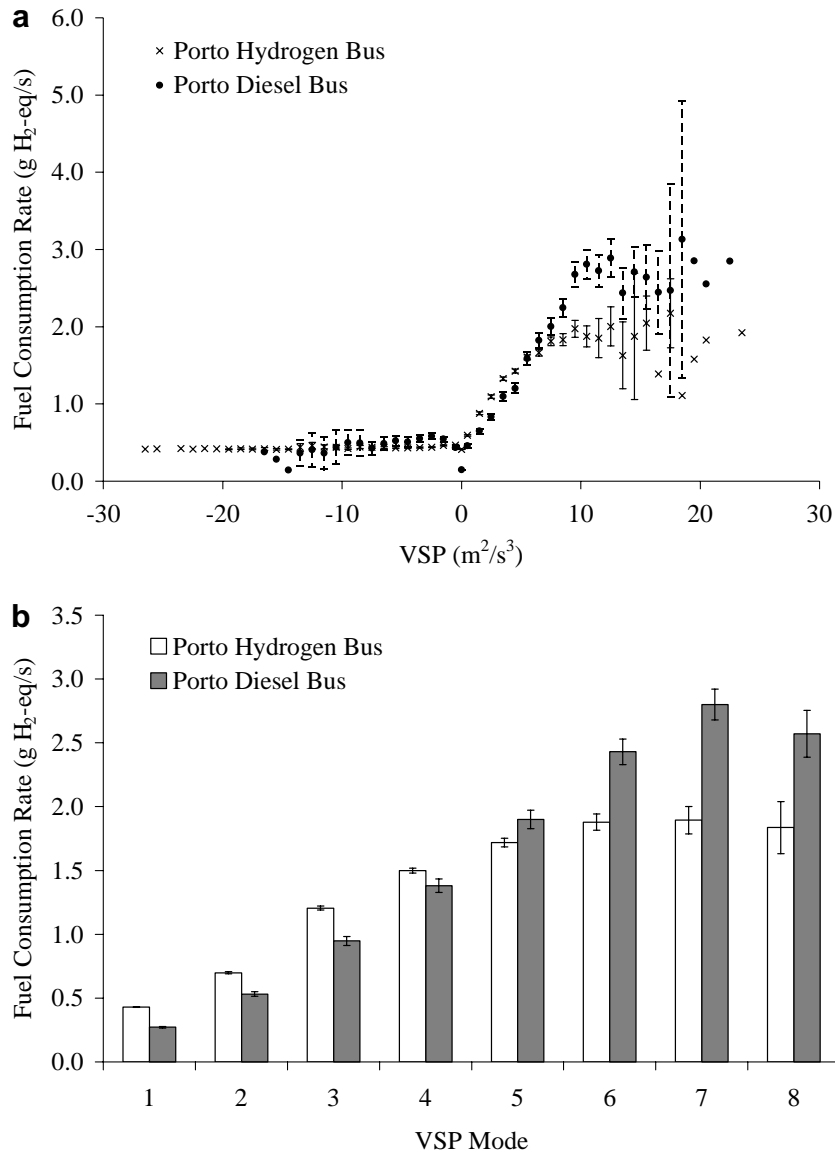


Fig. 3. Fuel consumption rate by VSP mode for Porto diesel and hydrogen fuel cell buses: (a) VSP and average fuel consumption, with 95% confidence intervals and (b) VSP modal average fuel consumption rate, with 95% confidence intervals, for Porto buses.

increase with increasing VSP mode. For three of the eight modes, the average fuel consumption rates are not statistically significantly different. For six of the eight modes, the difference in average fuel consumption rate between the AATA and Porto buses is less than 15%. Thus, for most modes, the differences are not substantial even if they are statistically significant. Therefore, the fuel consumption rates for the AATA and Porto buses appear to be similar.

A comparison of modal fuel consumption rates between the Porto diesel and fuel cell buses is shown in Fig. 3b. Overall, the hydrogen bus fuel consumption rates are less sensitive to high values of VSP. However, they are larger than the diesel fuel consumption rates at low VSP values but lower at high VSP values. The fuel cell bus weighs approximately 2 tonnes more than the diesel bus, and dumps power at low loads to maintain a minimum fuel cell power output. This accounts for the higher fuel consumption in lower VSP modes. The fuel cell bus tested here was designed to demonstrate the reliability of system components but was not optimized

Table 3
Summary of trip fuel consumption prediction errors for the validation data sets

Data source	Fuel type (units)	Trip code	Measured trip fuel consumption	Fuel consumption prediction error	
				VSP approach (%)	VSP and passenger load approach (%)
AATA	Diesel (l)	1	13.09	0.8	N/A
		5	26.05	10.6	N/A
		8	31.19	−9.5	N/A
		14	19.37	3.4	N/A
Porto	Diesel (l)	3	3.96	9.0	0.6
		6	5.45	−7.3	0.3
		9	5.82	−8.7	−6.4
		12	5.85	−2.3	4.4
		14	4.67	2.2	0.04
	Hydrogen (kg)	3	1.89	−0.8	N/A
		6	1.66	2.6	N/A
		9	1.86	−0.8	N/A

Note: “−” represents underestimate and “N/A” represents no data available.

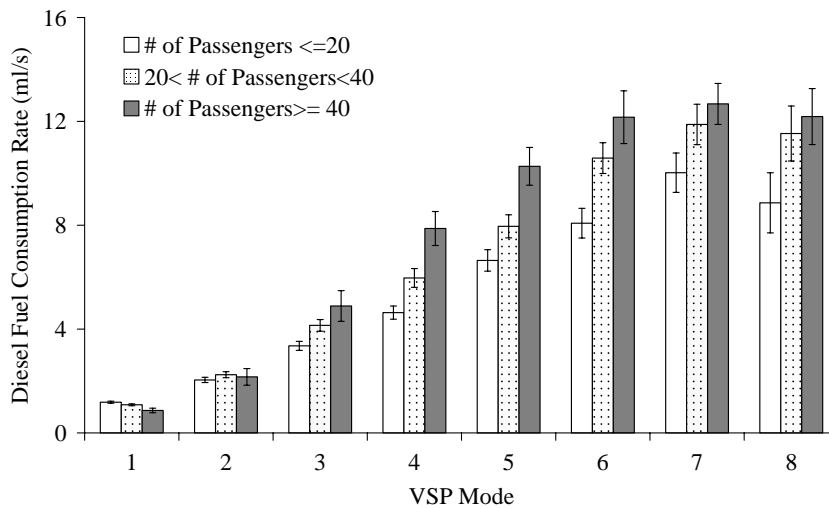


Fig. 4. VSP and passenger load modal average fuel consumption with 95% confidence intervals for the Porto diesel bus.

for efficiency. However, when operating at higher VSP values, the fuel cell bus appears to have higher efficiency. For this particular application, VSP mode 1 plays an important role because it includes idling and coasting – two important driving modes in urban buses. Therefore, small differences in mode 1 can have direct impacts on the overall performance of a given transit bus on an urban route.

5.3. Emissions evaluation

Fuel cycle and vehicle energy use and emissions, and their differences, for both hydrogen and diesel fueled buses are given in Table 4. Since hydrogen is a carbon-free fuel, hydrogen fuel cell vehicles produce only pure water as exhaust (Colella et al., 2005). Modal tailpipe emissions of the AATA buses are quantified elsewhere (Zhai et al., 2006). Tailpipe emissions reductions achieved by replacing conventional diesel buses with hydrogen-fueled buses are quantified, as are differences in fuel cycle emissions. The estimated change in energy consumption is also given. The results indicate that substituting hydrogen produced from steam reforming of

Table 4

Comparison of energy and emissions based on fuel cycle and tailpipe emissions: hydrogen versus diesel bus

Energy or pollutant	Stage	Energy or average emission ^a		Overall change (%)
		Hydrogen	Diesel	
Energy (MMBtu/cycle)	Fuel cycle	0.136	0.033	+51.4
	Driving cycle	0.185	0.179	
	Fuel cycle + driving cycle	0.321	0.212	
CO ₂ (g/g H ₂ -equiv. ^b)	Fuel cycle	12.5	1.6	+11.6
	Tailpipe	0.0	9.6	
	Fuel cycle + tailpipe	12.5	11.2	
CO (10 ⁻² g/g H ₂ -equiv.)	Fuel cycle	0.33	0.13	-91.6
	Tailpipe	0.00	3.80	
	Fuel cycle + tailpipe	0.33	3.93	
NO _x (10 ⁻¹ g/g H ₂ -equiv.)	Fuel cycle	0.07	0.04	-95.5
	Tailpipe	0.00	1.50	
	Fuel cycle + tailpipe	0.07	1.54	
HC ^c (10 ⁻³ g/g H ₂ -equiv.)	Fuel cycle	1.4	0.9	-65.0
	Tailpipe	0.0	3.1	
	Fuel cycle + tailpipe	1.4	4.0	

^a Estimates of energy consumption and emissions of the fuel cycle for hydrogen derived from steam reforming of natural gas and for diesel fuel are based upon the GREET model (Wang, 2001). In-use vehicle energy consumption is estimated based on the modal fuel use models of this paper, applied to a typical driving cycle in Porto, Portugal. The tailpipe emissions for the diesel buses are estimated from the modal emissions model of Zhai et al. (2006).

^b g H₂-equiv. refers to the energy-equivalent mass of hydrogen in grams, when comparing diesel and hydrogen fuels.

^c HC average emission in fuel cycle only refers to volatile organic compounds.

methane versus diesel as the basis for transit bus service may result in an increase in energy consumption and CO₂ emissions but substantial decreases in HC, CO, and NO_x emissions as well as particles (although not addressed within the present study). The fuel cycle emissions for hydrogen (H₂) product might be reduced in the future pending alternative technologies, with a possible cost trade-off.

6. Conclusions

The VSP approach, which integrates the effects of speed, acceleration, and road grade, into a single parameter, is able to explain a substantial portion of variability in fuel consumption. Relative variations in the VSP-based modal average fuel consumption for AATA buses in the US and the Porto diesel buses in Portugal were found to be similar. VSP-based modal average fuel consumption for the hydrogen fuel cell bus had smaller relative variability when compared to diesel buses. However, the fuel cell bus was not optimized for fuel economy, and thus additional work is needed to characterize fuel cell buses as the technology improves.

The VSP modal approach was shown to produce trip fuel consumption estimates that are accurate to within plus or minus 10%. The modal approach can be improved by further stratification based on passenger load, where such data are available.

The VSP-based modal approach is useful for characterizing bus trips and their fuel consumption. This approach should be further evaluated by application to a larger number of vehicles, as well as to a variety of fuel and propulsion systems. Furthermore, the VSP-based approach is a practical means via which to evaluate the effect of driving patterns on total fuel consumption and thus could be used to support policy analyses aimed at improving real-world fuel economy and air quality. Since the results here are based on a very small number of buses, data for more buses are needed.

Overall fuel cycle and vehicle energy consumption may increase if diesel fuel is replaced with hydrogen obtained from steam reforming of methane. Although CO₂ emissions may increase, substitution of hydrogen versus diesel buses may significantly decrease emissions of CO, NO_x and HC.

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